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LAKE KIVU EXPEDITION: GEOPHYSICS, HYDROGRAPHY, SEDIMENTOLOGY

(Preliminary Report)

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TECHNICAL REPORT

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Approved for Distribution Arthur E. Maxwell

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Provost

INTRODUCTION

In March 1971, seven members of the Woods Hole Oceanographic Institution were engaged in a multidisciplinary study of Lake Kivu. This expedition represents part of a long-range program concerned with the structural and hydrographical settings of the East African Rift Lakes and their relationships to the Red Sea and the Gulf of Aden Rifts. The program started in May 1963 with a geophysical study on Lake Malawi (von Herzen and Vacquier, 1967). Several expeditions of our Institution into the Red Sea and Gulf of Aden area in 1964, 1965 and 1966 (Degens and Ross, 1969) provided detailed geological information on the "northern" extension of the East African Rift. And finally our study of last year on Lake Tanganyika closed a major gap in the program; it allowed us to outline a model on the evolution of a rift which starts with (i) bulging of the earth's crust, (ii) block-faulting, (iii) volcanism and hydrothermal activity, and which has its final stage in (iv) sea floor spreading (Degens et al. 1971). In the case of Lake Tanganyika, only the second stage of this evolution series has been reached, i.e. block-faulting. In contrast, the Red Sea and the Gulf of Aden had already evolved to active sea floor spreading, almost 25 million years ago. Somewhere along the line between Lake Tanganyika and the Gulf of Aden must lie the "missing link" of this evolution series.

Lake Kivu, almost 100 miles to the north of Lake Tanganyika is situated at the highest point of the Rift Valley and is surrounded by active volcanoes and geothermal springs. As recently as 1944, lava flows reached the lake shore. This lake was therefore, a natural choice to test our hypothesis on the origin and development of rifts. Furthermore, the occurrence of large quantities of dissolved gases, e.g., CO_2 and methane, represented an interesting geochemical phenomenon worthwhile to investigate.

Logistics support was provided by the Institute pour la Recherche Scientifique en Afrique Centrale (IRSAC). The IRSAC facilities near Bukavu served as a base of operation; this organization further assisted us in the arrangements for a vessel and local transportation. A geophysical observatory maintained by IRSAC also provided a useful base station for magnetic and gravity studies on Lake Kivu. It goes almost without saying that without the support of this organization, in particular its Director Dr. Peter Kunkel and his wife Dr. Irene Kunkel, the goal of our expedition could not have been achieved. It is our pleasure to acknowledge the assistance and cooperation by members of the U. S. Consulate at Bukavu and Kigali in particular Consul Sykes, and the U. S. Ambassador to Rwanda, Mr. Cyr.

In addition to the scientific members of the expedition, several colleagues participated in the study and analysis of the sample material, and assisted in the preparation of this report. George R. Harvey and William Steinhauer investigated the distribution of hydrocarbons in sediments and waters of Lake Kivu; Hisatake Okada, Susumu Honjo, and John C. Hathaway studied some of the sediment material by X-ray diffraction, energy-dispersive X-ray analysis, and electron microscopy.

OBJECTIVES OF OUR PROGRAM

It is well to remember that our Lake Kivu expedition was only a small segment of our long-range research efforts in East Africa. With regard to the geological and geophysical studies of the rift valley lakes, we attempt to elucidate the following questions:

(1) What are the ages of these lakes, as inferred from rates of sedimentation and total accumulation of sediments?

(2) What are the crustal structures beneath the lakes and their surroundings?

(3) Do the western rifts differ significantly in structure or age from the eastern rifts?

(4) Are the eastern and western rifts manifestations of a single tectonic development, or do they represent tectonic processes separated in time as well as space?

(5) Do the East African rifts show any consistent pattern of structure or age from north to south?

Concerning the hydrochemical and geochemical studies, crucial questions are the following:

(1) What is the source of the CO_2 and CH_4 dissolved in the deep waters of East African Lakes: volcanic, biological or diagenetic ?

(2) What is the relationship between hydrothermal activity, heavy metal discharge, and anoxic environments?

(3) What are the relationships between climatology and biological populations of the various lakes, as evidenced by the occurrence of distinct species of diatoms, dinoflagellates, ostracods, pollen and others in C^{14}- dated sediments?

(4) How do pluvial periods in tropical areas correspond with well-recognized glacial stages in Europe and North America?

(5) What are the most determining factors to account for the diversity of species observed in various East African lakes: water temperature, water chemistry, others?

GEOPHYSICS

Bathymetry

The major bathymetric features of Lake Kivu including the positions of the principal basins is illustrated in Figure 1a. The cruise track and station positions are shown in Figure 1. Heavy lines indicate the locations where oblique reflection and refraction profiles have been obtained by using radio-sonobuoys. Navigation was executed by dead reckoning and sextant angle readings to charted landmarks on shore. Additional control is provided by the matching of magnetic and seismic data at cruise track intersections. Navigational accuracy varies according to the weather conditions and the time of day. Typically it is better than 2 km under fair conditions, and perhaps as poor as ±4 km when it was stormy or during overcast nights.

Magnetics

Total magnetic field intensity is plotted in Figure 2a. The residual magnetic anomalies obtained by subtracting the regional field from the observed data is presented in Figure 2b. Except for the areas immediately adjacent to the land occurrence of Cenozoic volcanics (Fig. 2c), the magnetic field is smooth and the gradients are very gentle. There are a few isolated anomalies to the northwest of Idjwi, with amplitudes ranging between 50-100 gammas and wavelengths of 1-2 km. Along the northern coasts of the lake several elongated anomalies exist. They have a peak-to-peak amplitude of just over 300 gammas, and trend NE-SW, almost parallel to the direction of the rift.

Although there is a weak NE-SW trend, the magnetic anomalies do not exhibit a pronounced lineation pattern typical of the mid-ocean ridge provinces. However, this should not be taken as conclusive evidence for the absence of sea-floor spreading because we are only looking at an area that extends 15 km in a direction normal to the rift. Any rift-type lineations would also be subdued since the rift axis is sub-perpendicular to the earth's field in low magnetic latitude, and the pattern may be partially or totally erased by subsequent heating through Cenozoic volcanism.

On the other hand, many of the observed anomalies can be adequately explained in terms of local geology, for example as the magnetic effects of basaltic flows of appropriate dimensions, and of step faults in the magnetic basement. The susceptibility contrasts are estimated to be high, in the range of 10^{-1} to 10^{-2} emu.

There exist therefore at least two alternative interpretations to the magnetic pattern, and it should be emphasized that both interpretations are consistent with observations, and that sea floor spreading is neither precluded nor conclusively established.

Seismic Profiles

The profile of Figure 3 is a traverse from a point just offshore northwest of Idjwi across the Northern Basin to Goma. The shallow portions of this profile exhibit very rugged topography, and are completely devoid of any deposits. In the deeper Northern Basin, there are sequences of well-bedded, slightly folded sediments, reaching to a thickness of about 400 m. Near the southern edge of the basin, a very peculiar echo some 400 m in lateral dimension and 80 m in vertical extension is observed emanating from the lake bottom. It is acoustically transparent, and partially masks the subbottom reflections. We interpret this to be due to hydrothermal activity beneath the lake resulting in the release of gas bubbles and solutions rich in dissolved minerals to the bottom waters. Such hydrothermal jets are thus considered a potential source for the nutrient salts in the lake. Similar records have been obtained by de Bonitatibus et al. (1970) in the Gulf of Pozzuoli, and the fumaroles causing them have been photographed by Palumbo et al. (1970). Because such bottom expressions of hydrothermal activities are highly localized, they are very difficult to observe by spot-sampling procedures like hydrographic casts. The spikes that have been found in the heavy metal distribution curves for the lake waters (see Fig. 6 c) are perhaps indicative of the injection of mineral-rich hydrothermal solutions from the bottom, the injected solution being subsequently trapped in the stratifications of the water column.

The youthfulness of the lake is attested to by the sediment distribution pattern. There are extensive areas over which the basement beneath the lake is exposed. The Northern Basin, presumably three to four times as old as any other basin elsewhere in the lake and therefore the most thickly sedimented, has an average sediment thickness of about 300 m. The rate of deposition, dated by radiocarbon method, is 25 $cm/10^3$ yr. If one assumes a mean sedimentation rate of 25 $cm/10^3$ yr, this would imply an age of 1.2 million years. One should, however, bear in mind that surface sediments on which this rate has been determined, contain about 90% water. Since more deeply buried sediments have generally less interstitial water (10 to 50%), the real age of the lake might be considerably higher. In view of the fact that the greatest thickness of sediments observed in the Northern Basin exceeds 500 m (see Fig. 9b) a Pliocene age of the Northern Basin is likely.

Heat Flow

Heat flow was measured at 5 localities through the bottom of Lake Kivu. Values ranged over one order of magnitude, from 0.4 to 4.4 μ cal/cm^2 sec, which are respectively below and above average for the earth on the whole, and other rift valley lakes in particular (Von Herzen and Vacquier, 1967; Degens, et al., 1971). Vertical temperature profiles in the lake show sharp stepwise changes in water temperatures below 200 m depth, suggestive of possible subsurface discharges of hydrothermal waters into the lake. These and the possible effects of variable bottom sedimentation rates may explain the large range in the measured values, suggesting that at least some may not represent the equilibrium geothermal flux. More definitive statements may be possible after sedimentation rates and correlations between coring stations have been determined.

Gravity

Gravity was measured at some 60 localities on land around the lake shores and in profile approximately 150 km normal to the trend of the rift valley to either side of the lake at 10 km distance intervals (Congo and Rwanda). The data in profile extended across the rift valley mountains, in contrast to previous profiles of more limited extent (Evrard and Jones, 1962), so that the deep structure beneath the lake may be deduced. The accuracy of the measurements are expected to be about $\pm$5 mgal, as determined by the field altimeter used to determine station elevations. The gravity values will be reduced to anomaly values and structural interpretations made as soon as charts to determine accurate station locations become available.

HYDROGRAPHY

Stratification

The distribution of the four principal cations, i.e. magnesium, calcium, potassium and sodium in waters from different stations is illustrated in Figure 6. Two main features come to light (i) the increase in salt content with water depth in a somewhat stepwise fashion, and (ii) the relatively uniform concentration level at a given water depth independent of the geographic position of the water station. This suggests that a well-developed stratification pattern exists across the lake, and that this stratification is maintained because of the pronounced salinity (i.e. density) differences between the various water layers. The smoothness of the curves, as emphasized by the zipatone pattern, can best be explained by diffusion processes across the various boundaries. This explanation receives support from the temperature profile shown in Figure 5 which, below the O_2/H_2S interface, in shape closely resembles the distribution curve of, for instance, potassium. The temperature distribution in all water stations is summarized in Figure 7 and again we notice the same trend: (i) increase of temperature with depth (below the O_2/H_2S interface), and (ii) no significant temperature differences among the various stations.

The principal cause of stratification is related to hydrothermal activity. Warm waters rich in dissolved minerals are released from the lake bottom. Their high salinity more than offsets the temperature effect on density and they, therefore, spread without significant mixing from the areas of discharge across the whole lake. On geophysical grounds (see Fig. 3) we believe that a series of hydrothermal "jets" located in the Northern and perhaps Eastern Basins are the outlets of these saline solutions. Based on hydrographic data (Gillman, 1933) we estimate that the discharge rate is presently on the order of 2.5 km^3 per year. Using this figure it would take almost 300 years to fill Lake Kivu to its present water level. Expressed in a different way, the mineral-rich bottom waters will emerge after 300 years at the surface of Lake Kivu providing that the stratification pattern is not severely altered as a result of drastic changes in the quality or quantity of the ejected hydrothermal solutions.

Such a hydrographic situation has certain ecological implications. Not only will the salinity of Lake Kivu surface water progressively increase over the next few hundred years, but the contributions of substantial amounts of nutrients and certain heavy metals (Fig. 6) will lead to eutrophication and will produce environmental hazards we are so familiar with in polluted areas. The levels of ammonia, phosphorus, dissolved organic carbon, and silica (Fig. 6; Table 4) are remarkably close to those present in ordinary sewage. The amount of hexane-extractable organics is on the order of 30 mg/l in deep waters; amino acids range between 10 and 40 mg/l and the sugar content is approximately 1 mg/l.

This forecast should be taken seriously, because sediments beneath Lake Kivu give ample evidence that the environmental conditions we predict for the near future existed several times in the recent past and may have lasted for periods up to a hundred years.

Table 4

Dissolved Organic Carbon In:

Lake Kivu (St. 10) Depth (m)	Lake Kivu (St. 10) Concentration (mg/l)	Lake Tanganyika (St. 15) Depth (m)	Lake Tanganyika (St. 15) Concentration (mg/l)
0	30	2	38
100	28	50	37
200	15	75	36
200 (dupl.)	15	100	11
300	14	125	14
400	41	900	25
420	26	1,000	45
440	22	1,150	38

Dissolved Inorganic Carbon

CO_2 concentrations are constant from the surface to the O_2/H_2S interface which lies consistently at a depth of between 50 and 60 m. Surface concentrations in the northern basin cluster around 12.6 mmole/kg of water, while those on the southeast side of Idjwi lie around 13.7 mmole/kg. The difference is significant, implying either or both of the following: (i) more CO_2 is produced in the north, (ii) the fresh-water dilution is greater in the south. It should be noted that the surface concentrations are six to seven times those in sea water.

Below the O_2/H_2S interface CO_2 concentrations rise drastically with increasing depth, probably reaching values greater than 100 mmole/kg in the deepest part of the lake. The highest value measured thus far is 93.6 mmole/kg at a depth of 350 m. This value is a lower limit, however, because some loss of CO_2 upon sampling could not be avoided in this case. We have a few samples which did not incur loss but have not yet been analyzed.

As is the case with our CO_2 measurements we have, at this time, reliable C^{13} measurements only for the near-surface waters. One fact becomes very apparent from these data: the surface water is enriched in C^{13} by 10 to 14 parts per thousand relative to inflowing river water. This great a difference cannot be caused by high organic productivity which preferentially removes C^{12} from the water. Rather, the greater part of this difference must be due to a source of inorganic carbon, rich in C^{13}, in the lake. A deep location of this source is suggested by the CO_2 profile.

Dissolved Gases

Much speculation exists as to quantity and origin of dissolved gases present in Lake Kivu. We have tried to elucidate this problem and the first tentative results are given below.

At a few stations we analyzed the dissolved gases released from water samples brought to the surface at _in situ_ pressure. This was done on a Carle Instruments BASIC™ gas chromatograph immediately after recovery of the samples. Up to six gas samples were analyzed from each water sample, including the first few μl released just below _in situ_ pressure and the last portion of gas evolved at atmospheric pressure. The major constituents are CO_2 and CH_4. H_2S and N_2 are present in relatively minor amounts. The CH_4/CO_2 ratio in the released gas changes greatly as the gas exsolves. CH_4 is predominant at first and then decreases rapidly. CO_2 is minor at first but soon becomes the major part of the gas released. An example of the change in the CH_4 and CO_2 proportions during gas release is shown in Figure 8. Approximate CH_4/CO_2 ratios and gas contents of the water at four depths are shown in Table 2. Samples from less than 300 m depth yielded only small quantities of gas at atmospheric pressure. The data in Table 2 suggest that, while the CH_4/CO_2 ratio changes with depth, the content of CH_4 per unit volume of water changes little. Based on these data and the lake's bathymetry we estimate that the water below 300 m in Lake Kivu contains 45 km^3 of CH_4 releasable at NTP, corresponding to 32 million metric tons of methane. Compared to the reservoir of a major gas field, such as the North Sea, which has been estimated to run in the order of a few billion tons of natural gas, the gas potential of Lake Kivu is comparatively small. However, it should be remembered that the estimates on Kivu are based solely on the gas present in the lower 150 m of the lake. This gas can be readily extracted, and it is constantly renewed by biological and geochemical means. We have so far no reliable method of distinguishing between biological and geochemical production and of estimating the effectiveness of the recharge. We can only conclude that the quantity present below 300 m has probably accumulated in less than 100 years.

In Table 3 we present gas chromatographic analyses of the hydrocarbon content of two water samples. Most notable is the presence of hydrocarbons with more than one carbon atom. These hydrocarbons (C_2 and up) have unquestionably been released from the sediment strata, since microbiological activities will commonly yield only methane. Nevertheless the high ratio of C_1/C_2 of 500 to 600 suggests that a substantial amount of the methane present in Lake Kivu waters has been generated by organisms.

BIOLOGY

Productivity Measurements

The upper 50 m of Lake Kivu are rich in planktonic plant life. Our measurements of photosynthetic production of organic carbon showed a value of more than 1.5 $g/m^2/day$. Part of this organic material and part of the nutrients are remineralized in the oxygenated surface waters. As a first approximation we estimate that 90% of the primary production is recycled within the upper 50 m, that is, of the annual production of 550 g C/m^2 only 55 g C/m^2 sink below the O_2/H_2S boundary; the rest becomes oxidized or metabolized in the surface waters. Aside of plants (predominantly diatoms; Nitzschia spp.) plankton tows revealed the presence of large amounts of zooplankton, principally one species of Calanus. Also the count of aerobic heterotrophic bacteria was unusually high in 20 to 50 m of depth.

Microbiology

The most striking microbiological feature of Lake Kivu is the unusually rich flora of methane and methanol oxidizing bacteria. Most of our isolates seem to represent new forms or new species not observed before, while the known types of microbial methane oxidizers appear to be absent. Over 70 isolated strains are under investigation. The reason for the abundance and large variety of different morphological types of these organisms is believed to be found in the unique chemical composition of the water of the various depths. This is especially true for the presence of heavy metal ions reaching concentrations that exert strong effects on life processes. The uniformity of the zooplankton we collected in vertical catches may be related to a similar effect.

In Lake Kivu, chemosynthetic fixation of carbon dioxide is likely to occur above and below the O_2/H_2S interface. Available electron acceptors are ammonia, nitrite, sulfide, and probably other reduced sulfur compounds. The anaerobic fixation of carbon dioxide by photosynthetic bacteria will not be of great significance at the conditions we encounter. The density of phyto- and zooplankton observed will limit the depth of light penetration to the aerobic surface layer. No distinct abundance fluctuations of microplankton were observed in the zone of oxygen deficiency and no layer of pigment microorganisms was found by macroscopic or microscopic examination of the water samples.

Mid-water sound reflections at a depth of 20 to 30 m are indicative of the presence of schools of fishes. No attempt was made to collect some of these fishes because of lack of proper fishing gear. The abundance of fish in the open lake is unknown; considering the local prevalence of human protein deficiency, a careful study on the occurence and behavior of fish is desirable. So far there are only 20 species of fish known from Lake Kivu compared to 400 in nearby Lake Tanganyika. This indicates an unstable ecology which is principally caused by hydrothermal and volcanic events, and their effects on the hydrography of the lake.

SEDIMENTOLOGY

Stratigraphy

A total of 10 cores were taken from various parts of the lake; the longest measured 11 m. Because of the high gas pressure developed in the sediments, some material was lost when the cores were brought to the surface. The longest undisturbed core section measured almost 4 m.

The stratigraphic record of three cores is shown in Figure 10. Sediment sections from below 350 cm were lost due to gas expansion and extrusion of sample, or were too disturbed to allow a stratigraphic correlation. At Stations 10 and 13, a layer of volcanic ash of about 1 m thickness was recovered; the exact stratigraphic position cannot be ascertained. Only so much we can infer that the ash occurs at a depth range between 350 and 580 cm, which is also the maximum depth penetrated at these two stations.

A 580 cm core recovered from Station 14 at a water depth of 330 ~~cm~~ m contained essentially the same stratigraphic units present in the top 180 cm of core 10 (Fig. 10). Below that depth, core 14 was completely filled with well-rounded pebbles principally of metamorphic provenance; the diameter of the largest pebble is 5.5 cm which is exactly the diameter of our core tube. We first suspected this deposit to be a turbidite; yet the lack of graded bedding and of other features we commonly associate with turbidites led us to conclude that we are dealing with an ordinary beach deposit; the presence of intact worm tubes, shell fragments and other organic remains was consistent with this explanation.

Three distinct sedimentary units can be recognized (Fig. 10). The uppermost unit, almost 130 cm thick is composed of brown and white layers; up to 50 individual layers per centimeter have been counted. On first sight, the brown layers have the appearance of limonite bands and they are more predominant in some sections than in others. On this basis we initially termed them "metal-rich" layers; this term proved, however, to be incorrect after a more careful mineralogical and geochemical investigation. We now know that these bands are rich in organic matter (up to 40%); they yield as much as 1.5 per cent hydrocarbons upon solvent extraction. The white layers are principally made up of diatoms and carbonates. We were surprised to find large amounts of coccoliths in some of the layers. Since coccoliths are so far only known from marine deposits , we can only conclude that these organisms have probably been brought in by birds; it is puzzling, however, that the species identified are from cold water environments.

The second stratigraphic unit is also finely laminated. The micro-lamination is even more spectacular and we counted up to 100 individual layers per centimeter. The dark brown jelly-like bands so predominant in the top unit are completely missing. Also, no coccoliths have been found so far in this unit; the examination, however, is not completed. At Station 10, the unit extends to 310 cm; the stratigraphic correlation to other cores can be seen in Figure 10. The frequent occurence of volcanic ash layers at the base of this unit can be considered an aftermath of a major volcanic eruption that produced the third stratigraphic unit (not shown in figure) which is essentially a tuff of approximately 1 m thickness. The poor recovery of sediments below the tuff bed is attributed to the porosity of the tuff which allowed gases to accumulate; upon raising the core to the surface, the gases were instrumental in ejecting most or all sediment material below the ash layer.

The radiocarbon age of the sediments at the base of core 9 (330 cm) is 11,600 years corresponding to 25 to 30 cm/10^3 years. In turn, the major volcanic event leading to the deposition of the 1 m tuff bed occured somewhere between 12,000 and 15,000 B.P. It is possible that this event coincides with the formation of the Birunga volcanoes to the North of Lake Kivu which caused a blocking of the Nile drainage system and resulted in the formation of Lake Kivu as we know it today. The inferred beach deposits at Station 14 with a radiocarbon age of 7,000 years would conform with this interpretation by showing that the water level at that time was about 330 m below the present water mark.

In this context it is interesting to point out that Lake Tanganyika has recorded in its sediments of the last 4,000 years some of the geological and hydrographic events that occurred during that time in Lake Kivu. Lake Tanganyika is connected with Lake Kivu by the Ruzizi river which formed in the recent past as a consequence of hydrothermal discharge at the bottom of Lake Kivu. In Figure 15 we bring the distribution of boron, manganese and $CaCO_3$ in the upper two meters of sediments of Lake Tanganyika (Station 3; see Degens et al., 1971). Boron is known as a sensitive indicator of volcanic activities; it is the first element to increase in concentration. A few hundred years later, manganese starts to increase, whereas carbonate deposition occurs almost 2,000 years after the first "wave" of boron became incorporated into the sediment. The geochemical pattern is a reflection of the differences in the solubility and deposition characteristics between these three compounds; namely, boron can readily be incorporated by clay minerals the moment it enters Lake Tanganyika waters. Manganese requires more time for concentration and precipitation as a mineral phase, while $CaCO_3$ formation requires saturation conditions in the water since carbonate deposition in Lake Tanganyika is principally non-biological. As a final note we like to point out that on the basis of fossil and mineral content some of the layers in Lake Tanganyika sediments can be correlated with sediment layers in Lake Kivu. This stratigraphic correlation, however, is possible only for sediments deposited over the last 3,500 years.

Mineralogy

Core 10 and 9 were examined by X-ray diffraction and electron microscopy. Remarkable is the lack of clay minerals in sediments of the Northern Basin. Most of the material is amorphous silica and pyrite which account for about 80 to 90% of the total. The remainder is calcite, high-magnesium calcite, aragonite, gypsum, bassanite and halite. In some of the white layers the carbonate content may be as high as 80%. The largest amount of calcium sulfate was between 5 and 10%. Noteworthy is the occurence of a few per cent halite in some of the samples which suggests higher salinity conditions at that particular time in the geologic past. The ash layers are commonly composed of volcanic glass (20%) plagioclase (bytownite-labaradorite; 30%), pyroxene (augite; 40%) and pyrite (10%). At the base of core No. 9 clay minerals (kaolinite; 50%; and illite, 10%) are abundant.

Geochemistry

Except for the hydrocarbon studies, the geochemical work is still in its infancy. So far we have analyzed the sediments for water content (80 to 90%), reactive iron (0.8 to 2.4%), total iron (4.4 to 10%), manganese (100 to 700 ppm), zinc (70 to 410 ppm) and copper (20 to 50 ppm). Most outstanding are the high zinc values for sediments of this kind. In view of the high abundance of zinc in the water (average 2 ppm) these values can readily be explained. In this context it is of interest, that zinc precipitates as ZnS (sphalerite) upon filtration of waters taken below the O_2/H_2S interface. The ZnS precipitates have the appearance of globules (1 μ in diameter) which are composed of numerous individual particles (Fig. 12) as revealed by electron microscopy. In the sediments, identification of zinc minerals is tentative because it is based only on optical properties of some minerals which exhibit high index of refraction, are isotropic, and have the morphological appearance of sphalerite. The brown to yellowish cast of these minerals suggest a high iron content. Because of the limited amounts of ZnS and the pyrite interference, identification by X-ray diffraction analysis was not possible. However, the material deposited on the filters gave the ordinary sphalerite pattern upon X-ray analysis. For illustration we also like to present some electron micrographs of pyrite framboids and some organisms found in the water column (Figs. 11 and 13) in Lake Kivu sediments (Fig. 14), and of aragonite precipitates in hot springs (Fig. 16).

Bitumens in Sediments and Water

Lake Kivu has been known for its methane content for many years. It was of interest to determine if this was purely of bacterial origin or represented an advanced stage of organic diagenesis leading to natural gas and petroleum. Therefore, sediments were extracted so as to reveal the total organic content. This extract was further fractionated, by standard procedures, to separate the various type of organic matter present, i.e., saturated hydrocarbons, aromatic hydrocarbons and asphaltenes. The water was extracted with nitrogen to reveal the natural gas content and with hexane to determine the hydrocarbons. The extracts were examined by standard gas chromatography techniques and compared with authentic standards.

Extracts from three depths of the sediment at Station 10 were fractionated and the chromatographs of some of the fractions are shown in Figures 8 and 9. The chromatograms show a typical array of biogenic hydrocarbons with a C_{odd}/C_{even} ratio of 1:10 to 1:20. There are homologous hydrocarbons missing in the chromatogram indicating the source to be the plankton of the lake or the plants of the watershed. A typical crude oil shown in Fig. 8 is the result of millions of years of physical, chemical and biological alterations and every resemblance to the original biogenic material has been eliminated. Thus, the shallow sediments of Lake Kivu contain no traces of a petroleum seep. The organic matter is very young or immature and resembles that found in most limnological studies. The highest hydrocarbon concentration measured in Lake Kivu sediments is 14,000 ppm.

The water analyses revealed the expected methane but also ethane, propane, butane, etc. up to the hexanes. Although, the ratio of methane to ethane indicates that the former is derived mainly from bacteria the presence of the higher gases is definitely not bacterial in origin but diagenetic. The quantities found are summarized in Table 3. The presence of these gases usually indicates a very mature petroleum deposit. None are biogenic in origin but are produced in the latter stages of maturation of organic matter.

We believe that there probably is some very old and mature petroleum trapped deep in the Lake Kivu sediments which may even have accumulated in the geologic traps so abundant in the Northern Basin (Fig. 3). The more volatile gases are capable of escaping and mixing with the water. However, we know of no formula of translating the extent of a gas seepage with the volume of a crude oil.

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TABLE 1

WATER ANALYSES

LOCALITY	Ca	Mg	K	Na	Cl	SO_4	ΣCO_2	NH_4	P	Si	$NO_3 + NO_2$
	(		mg/l			)	(m mole/kg)	(	μgA/l		)
Tanganyika(St.3;surface)	8.2	41.5	34.2	66.3	21	3.4	5.64	5.1	1.1	1.2	0.2
Tanganyika(St.3;460 m)	5.5	42.0	33.4	68.8	21	3.4	5.98	2.5	4.9	245	0.3
Tanganyika(St.3;1460 m)	5.2	41.0	32.8	66.3	23	2.5	6.38	2.0	5.2	315	0.2
Kivu (St.4;surface)	4.8	87	97.4	121.6	55		12.5	18	.8	231	1.9
Kivu (St.4;100 m)	64.0	147	145.4	192.0			29.3	487	18.8	424	.38
Kivu (St.4; 200 m)	83.1	182	178.8	244.6			42.0	1314	32.7	428	.27
Kivu(St.4; 350 m)	110.9	394	315.2	465.2			93.6	5460	53.2	1056	.48
Kivu (St.4; 440 m)	112.6	417	338.0	487.4			92.0	7105	54.8	1226	.32
Kakondo (Hot Spring)	82.2	53	56.6	179.6	80		29.7	109	3.9	627	1.4
Road Lwiro Kakondo Kaukula (Hot Spring)	85.5	60	67.4	226.0	63		21.9	116	1.7	896	3.3
Lwiro Creek	6.7	4.5	3.0	12.0	28		1.71	65	1.6	401	17.9
Kabindi Creek	2.7	1.7	3.0	14.4	4		1.69	74	1.0	245	18.4

TABLE 2

GAS ANALYSES

(Lake Kivu, Station 4)

Depth	First 40 cc*	Total Gas*	(V_{gas}/V_{H_2O}) 1 atm	(V_{CH_4}/V_{H_2O}) 1 atm
300	0.39	0.39	1.4	0.4
350	0.36	0.35	1.6	0.4
400	0.35	0.29	1.8	0.4
440	0.43	0.37	1.6	0.45

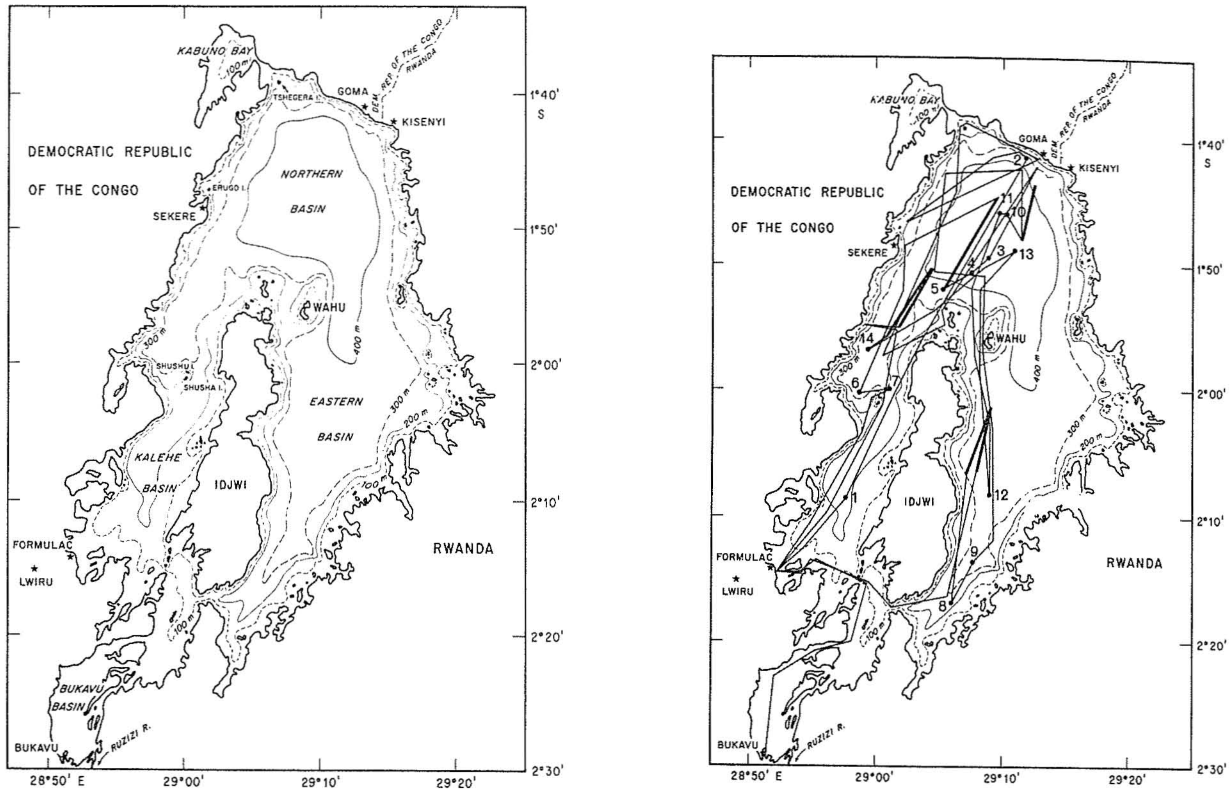
* $\frac{(CH_4)\ gas}{(CO_2)\ gas}$: released from 28.5 cc of water.

TABLE 3

GAS ANALYSES*

	Station 13 (300m)	Station 7 (250 m)
methane	650	530
ethane	1	1
propane	0.33	0.13
iso-butane	0.07	0.27
n-butane	0.04	trace
$C_5 + C_6$	0.61	trace

*Expressed in simple ratios relative to ethane = 1

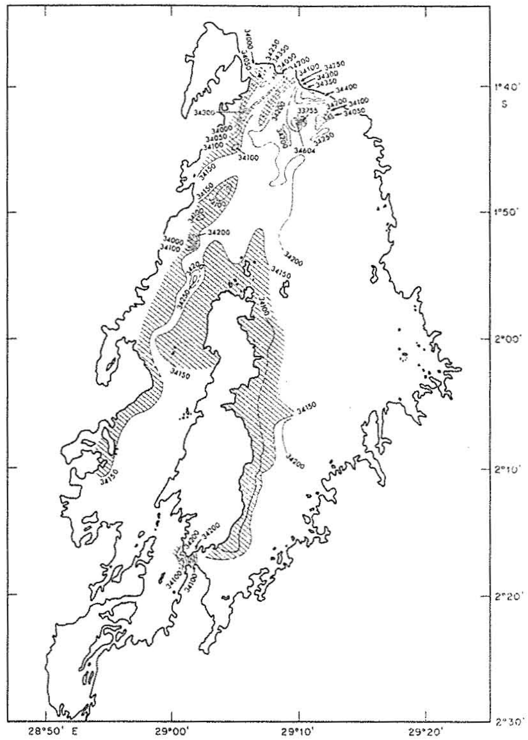


A B

Figure 1

(a) Bathymetry of Lake Kivu, showing the Bukavu, Kalehe, Eastern and Northern Basins. The greatest water depth of almost 500 m occurs in the central part of the Northern Basin.

(b) Cruise track and station positions. Heavy lines indicate the locations where oblique reflection and refraction profiles have been obtained by using sonobuoys. The tracks are confined to the western parts of the lake because permission to enter Rwandese waters was received only at the day of cruise termination.



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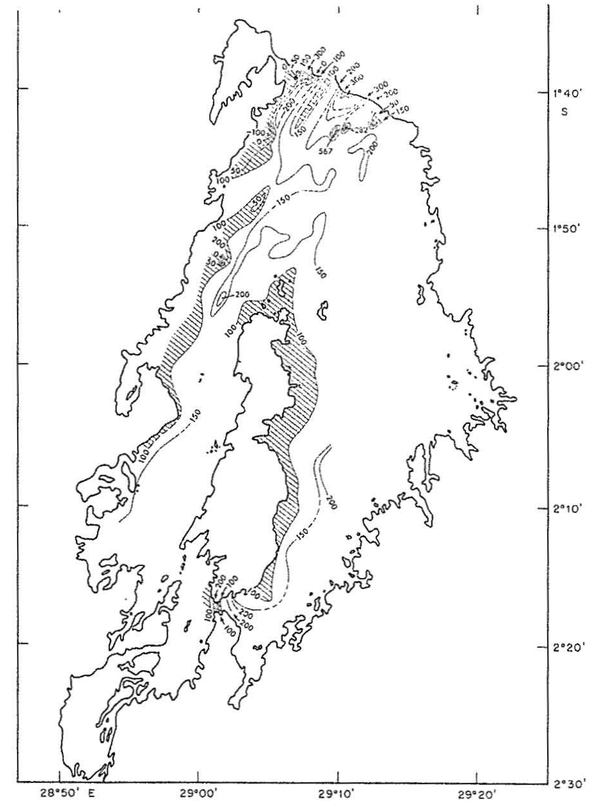

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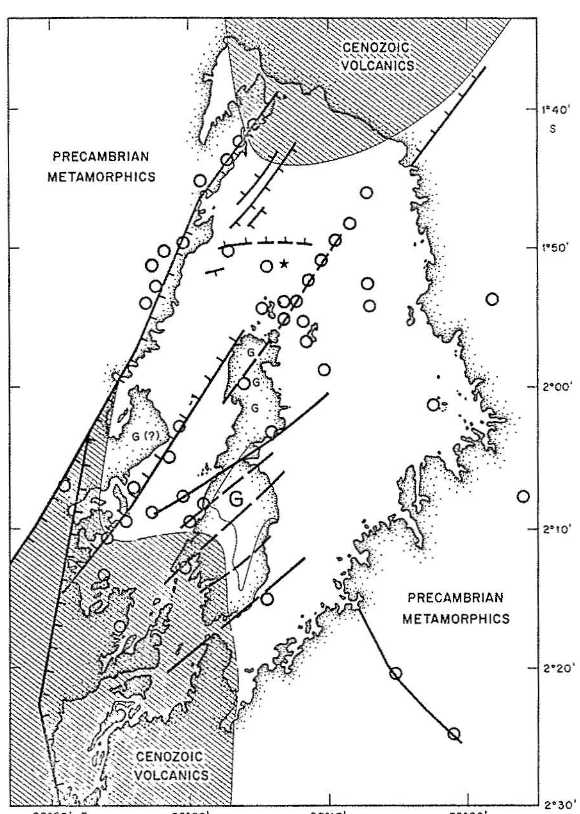


C

Figure 2

(a) Total magnetic field intensity. Contours are shown in gammas at 50-gamma interval except where the magnetic gradients are steep. Areas with values less than 34,150 gammas are shaded.

(b) Residual magnetic anomalies in Lake Kivu. Contours are shown in gammas at 50-gamma intervals except where gradients are steep. Areas with values less than 100 gammas are shaded.

(c) Geological structure of Lake Kivu. Circles represent earthquake epicenters (after Girdler _et al_. 1969; Wohlenberg, 1968; and Bramaecker, 1959). Faults are after UNESCO-ASGA (1968), Girdler _et al_. (1969), Guibert (1971), and the present work. The symbol G represents granite. Areas of Cenozoic volcanics are shaded.

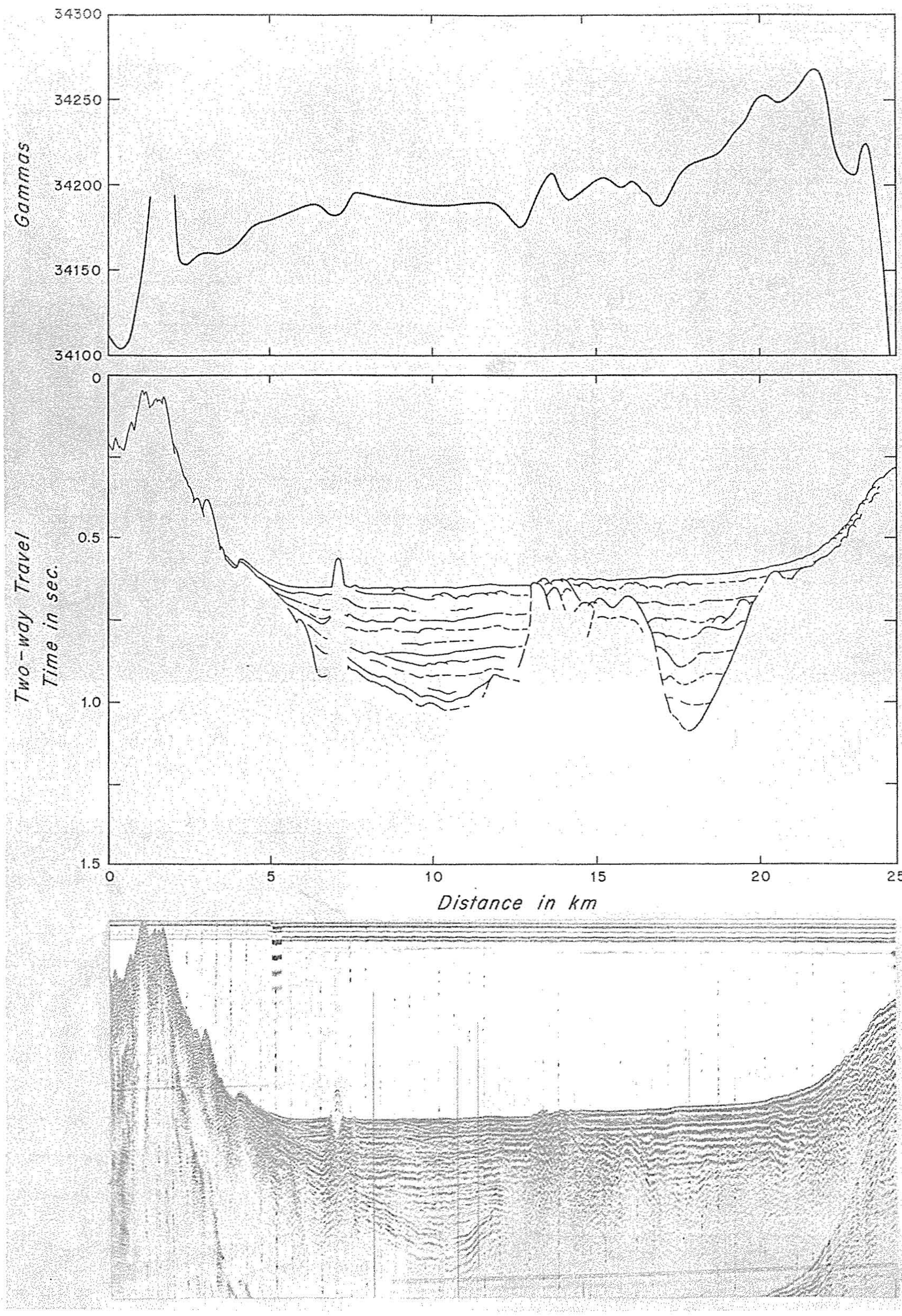
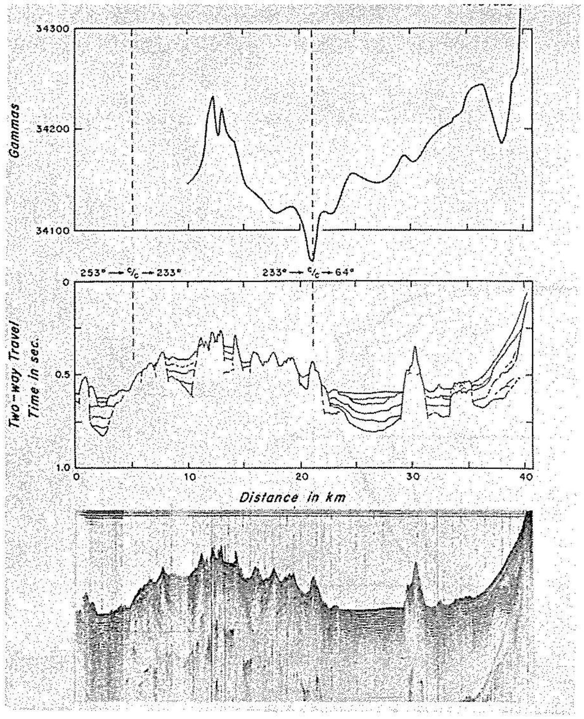


Figure 3

Continuous seismic reflection profile and total magnetic intensity along traverse from northwest of Idjwi across the Northern Basin to Goma. Note the peculiar echo emanating from the lake bottom at about kilometer 7 position and extending almost 80 m into the open water. This phenomenon can best be explained by discharge of hydrothermal solutions.



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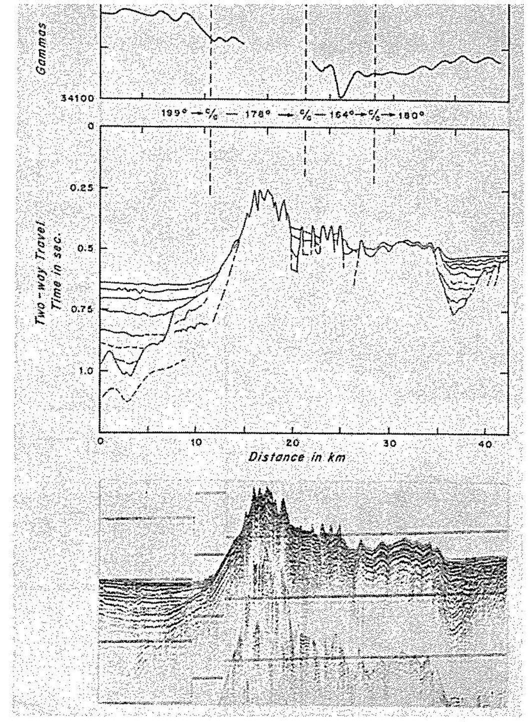

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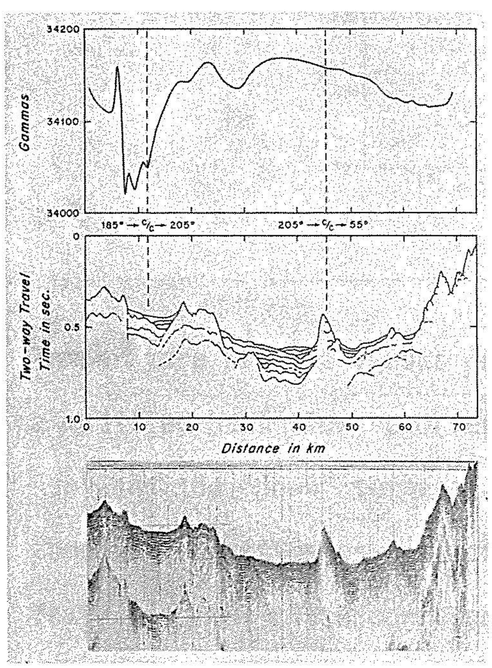

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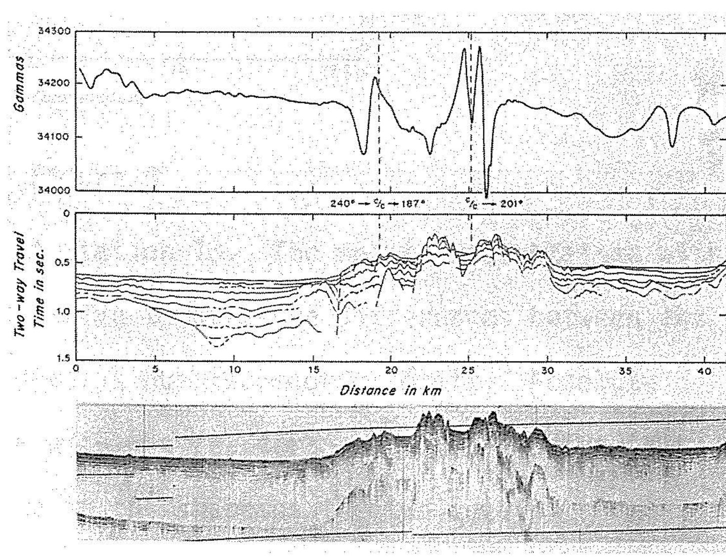

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Figure 4

Selection of typical seismic reflection profiles and magnetic profiles from Lake Kivu.

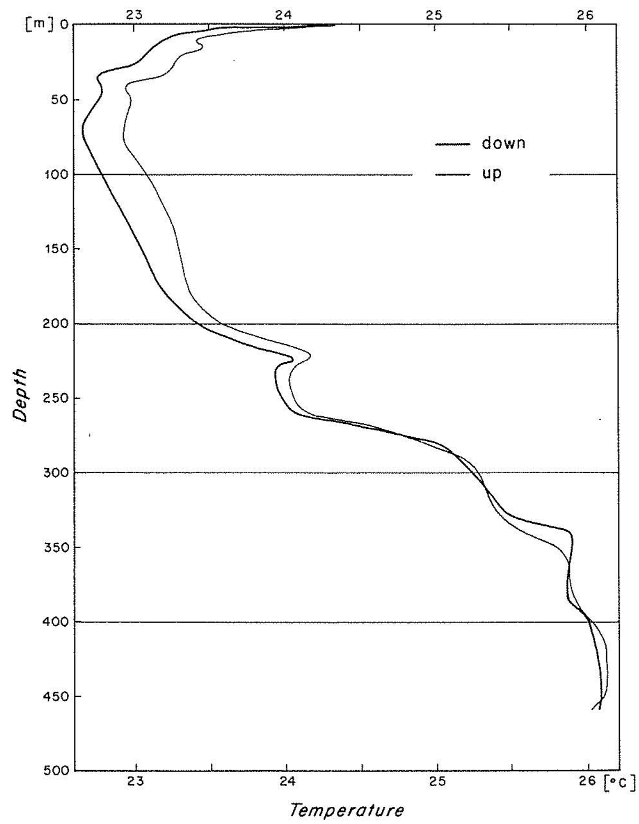
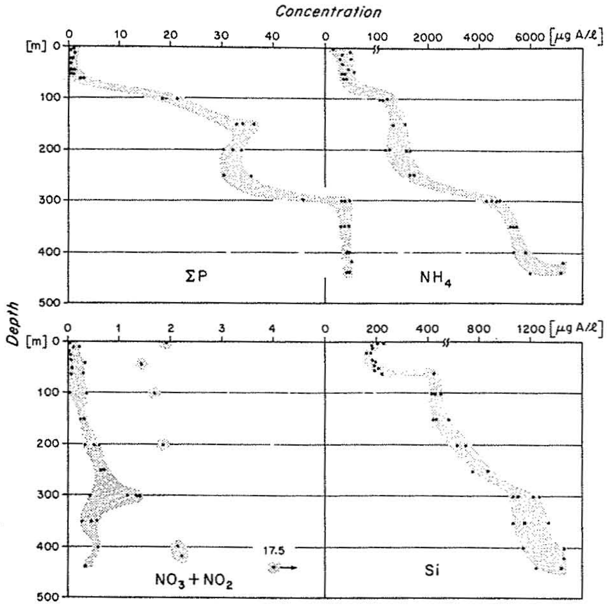


Figure 5

Temperature profile versus depth at Station 13. The record was obtained with a modified heat flow recorder. Relative temperature differences between the "up" and the "down" temperature curve is due to recorder drift. Absolute temperature estimates are accurate within a few tenths ^{0}C. The most outstanding feature is the close correspondence in the shape of the two curves.



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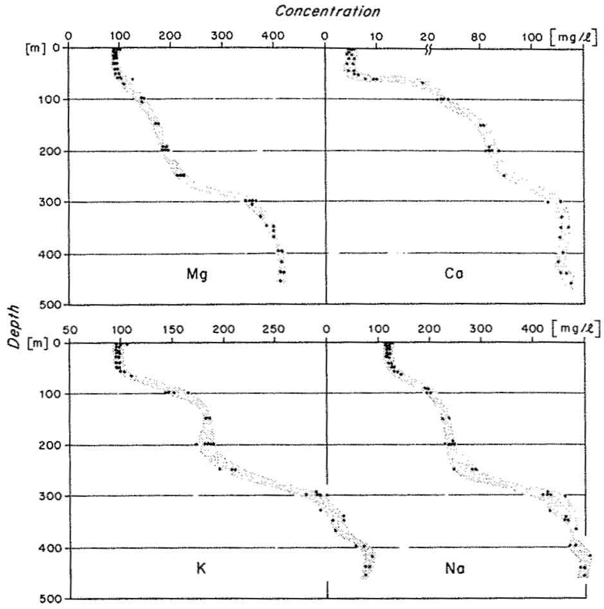

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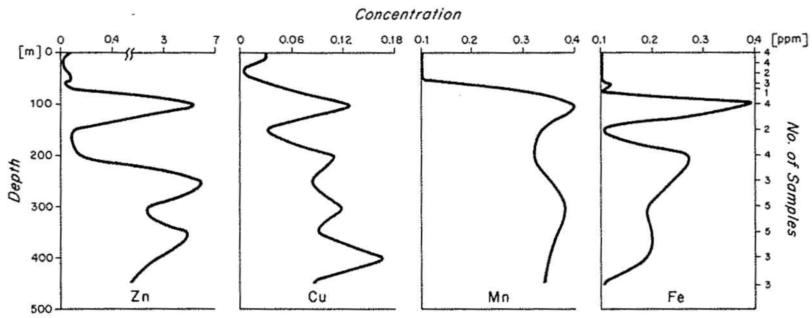

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Figure 6

(a) Distribution of nutrient minerals (P, NH_4, NO_3 + NO_2, and Si) in Lake Kivu water from Stations 2, 3, 4, 7, and 10. Two features are outstanding (i) the minor variation in concentration at a given depth among water samples from different parts of the lake (except for NO_3 + NO_2) and (ii) the systematic but almost stepwise increase in concentration with depth.

(b) Distribution of major cations (Mg, Ca, K, and Na) in Lake Kivu water from Stations 2, 3, 4, 6, 7, 9, 10, 12, and 13. The small variation at any given depth, and the stepwise increase in concentration are the most remarkable features.

(c) Distribution of dissolved heavy metals (Zn, Cu, Mn, and Fe) in Lake Kivu water.

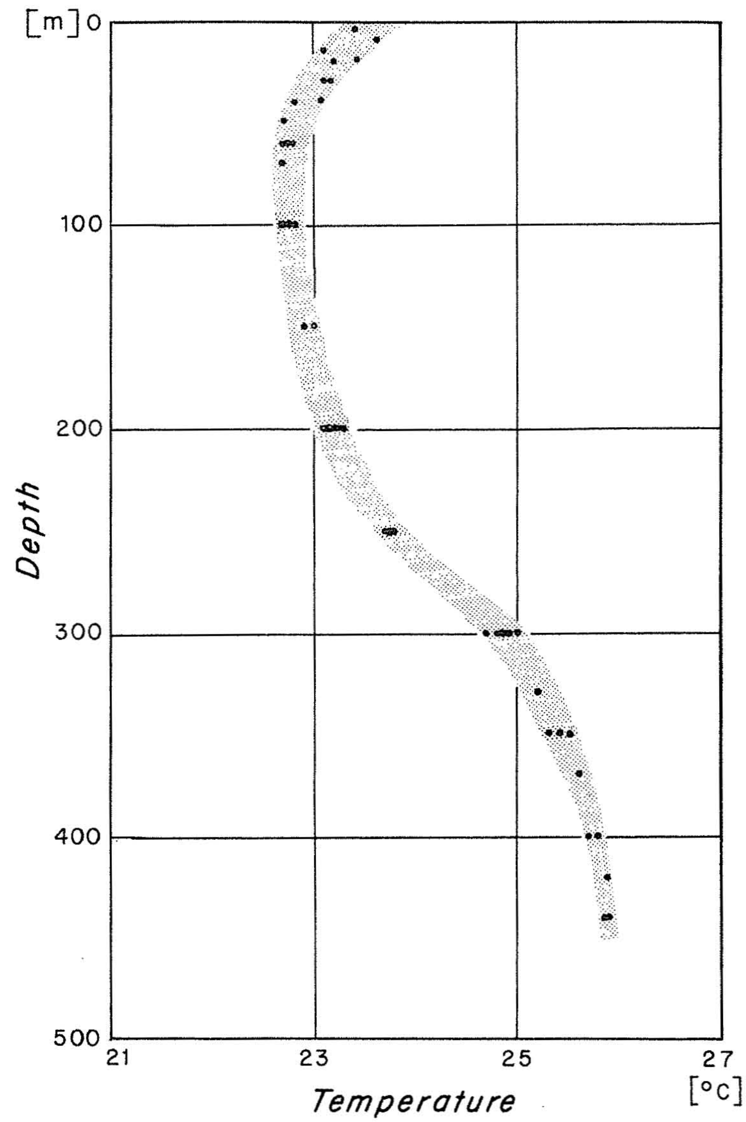


Figure 7

Temperature versus depth profile for all water stations. The measurements are accurate within 0.1 ^{o}C. Noteworthy is the increase in temperature with depth below the O_2/H_2S interface and the absence of significant variations among all samples at any given depth. The vertical spacing between samples is too large to reveal details of the kind shown in Figure 5.

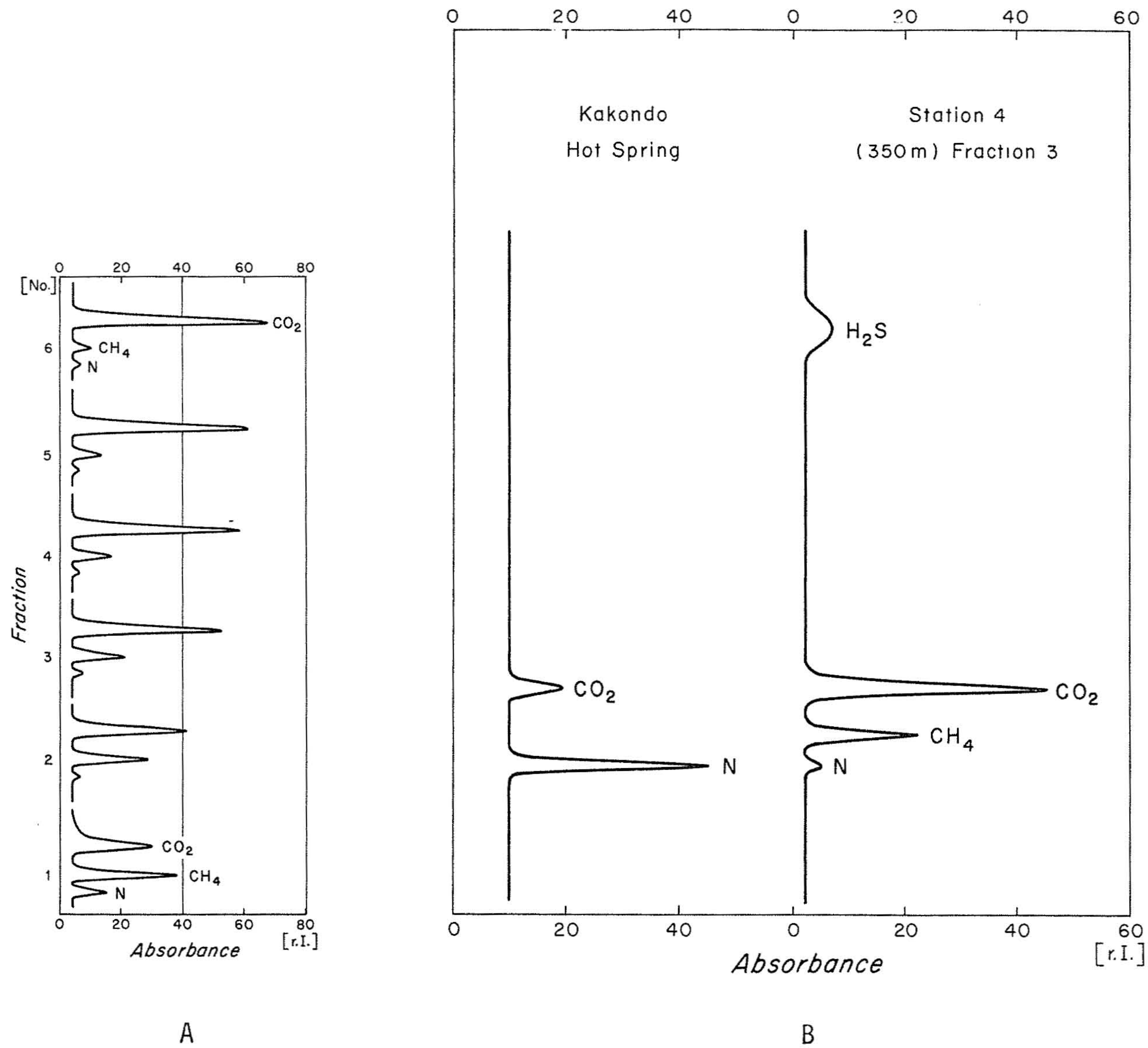


Figure 8

(a) Gas chromatographic records of one water sample (Station 4; 400 m) collected with an in situ-pressure sampler. The gas phase was extracted and measured until no more free gas escaped ($\sim$1 atm). Between successive fractions, 10 cc of gas were discarded and 40 μl of gas were subsequently injected into the gas chromatograph.

(b) Gas chromatographic records of gas liberated from (i) Kakondo hot spring, and (ii) Lake Kivu water. Note the lack of methane (CH_4) and hydrogen sulfide (H_2S) in the hot spring sample.

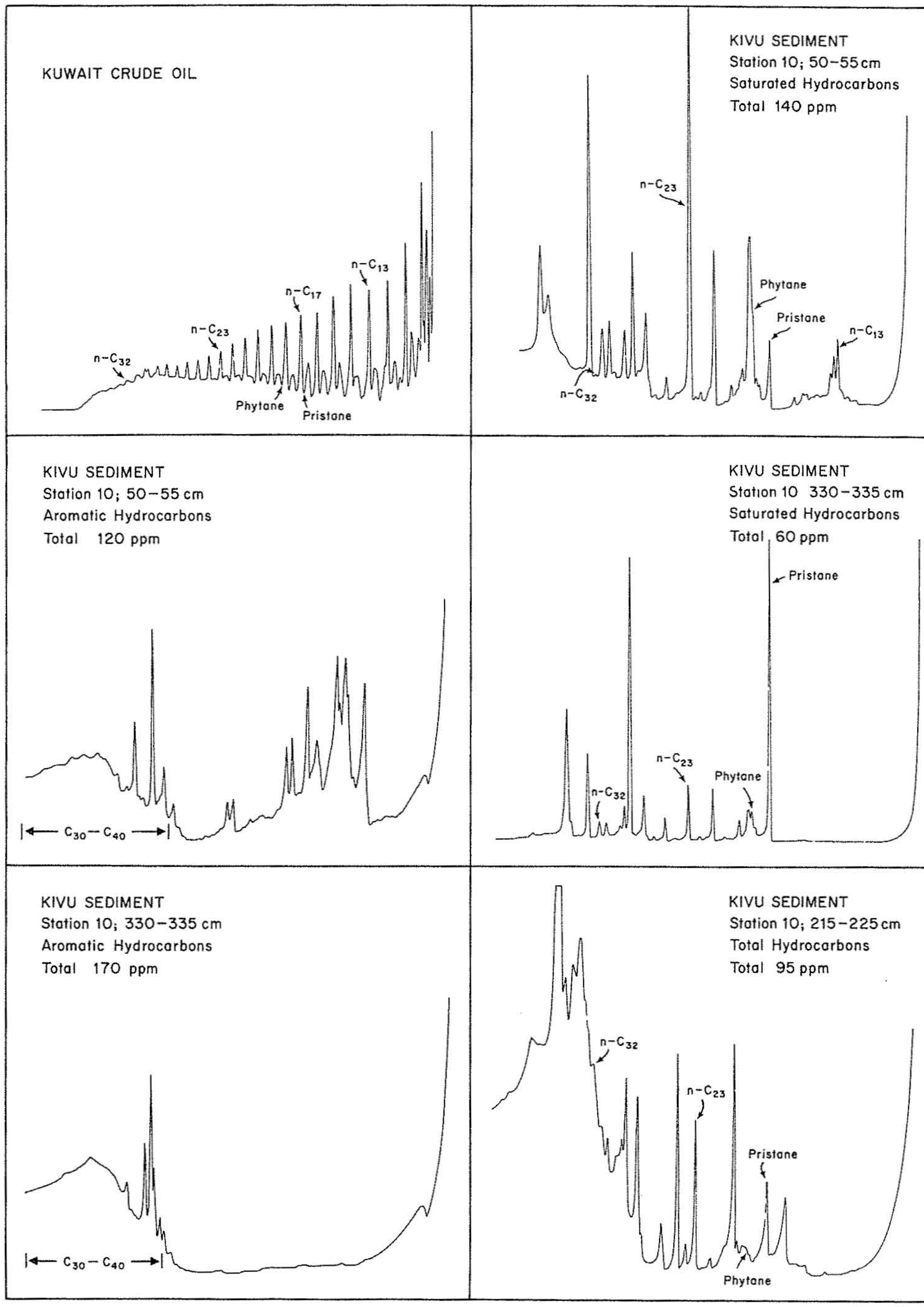


Figure 8 c

Gas chromatographs of hydrocarbons from Lake Kivu sediments and Kuwait crude oil.

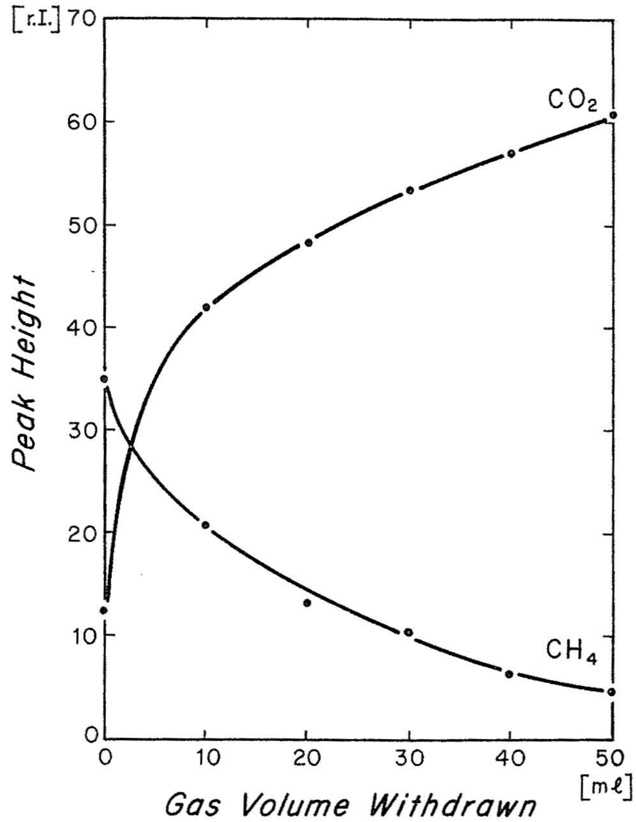
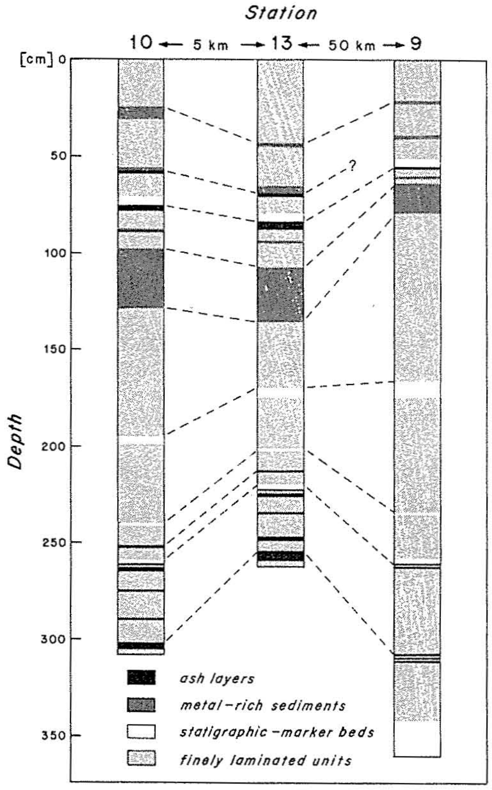


Figure 9

Peak heights of CO_2 and CH_4 versus amount of gas extracted from a water sample.



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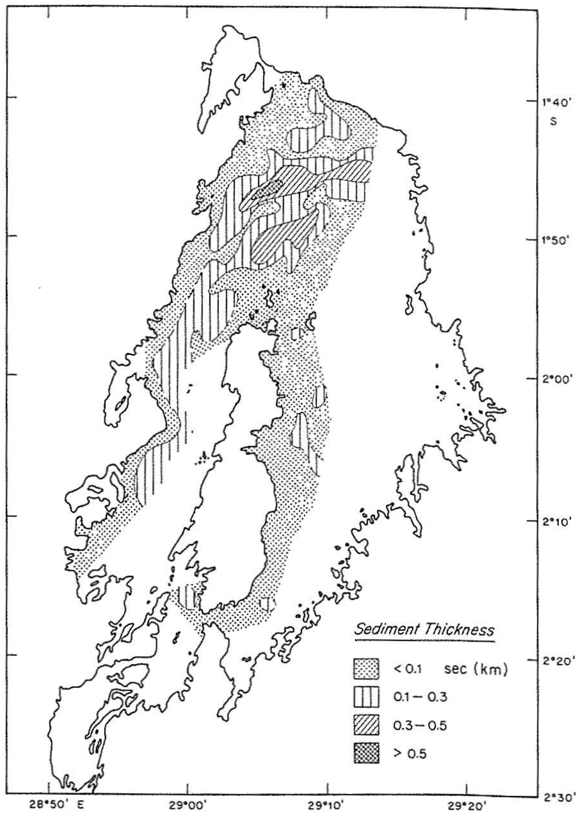

B

Figure 10

(a) Stratigraphic correlation of sediment cores 10, 13, and 9.

(b) Sediment distribution pattern in Lake Kivu. Sediment thicknesses are in seconds two-way travel time, or in km, if an average sound velocity of 2 km/sec is assumed.

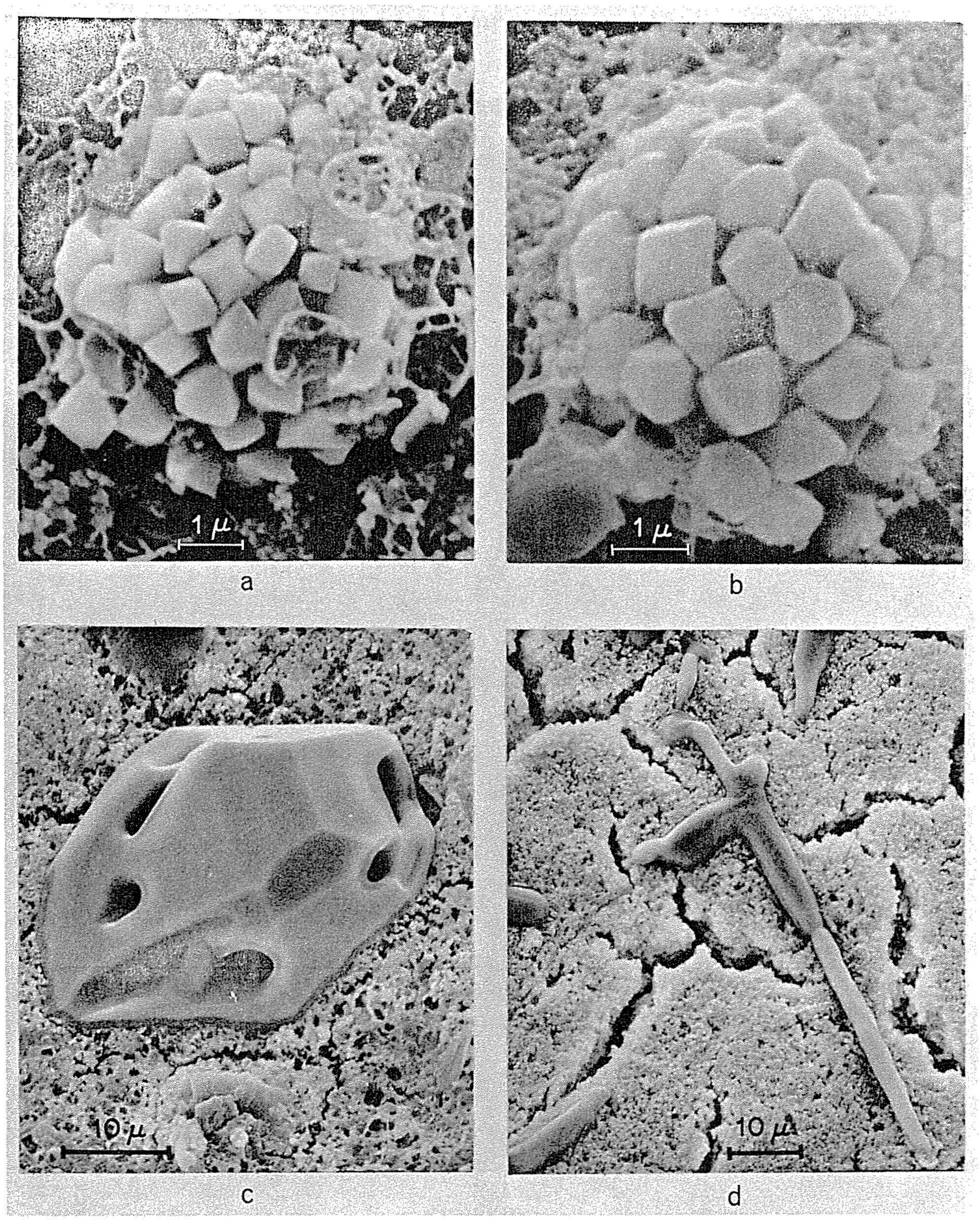

Figure 11

Electron micrographs of suspended pyrite framboids (a and b) which have been collected on millipore filters (Station 4; 100 m water depth). A sulfur crystal is shown in (c) and mineral mats, principally composed of zinc sulfide and amorphous sulfur, are shown in (d). In all instances, identification is based on X-ray diffraction and energy-dispersive X-ray analysis.

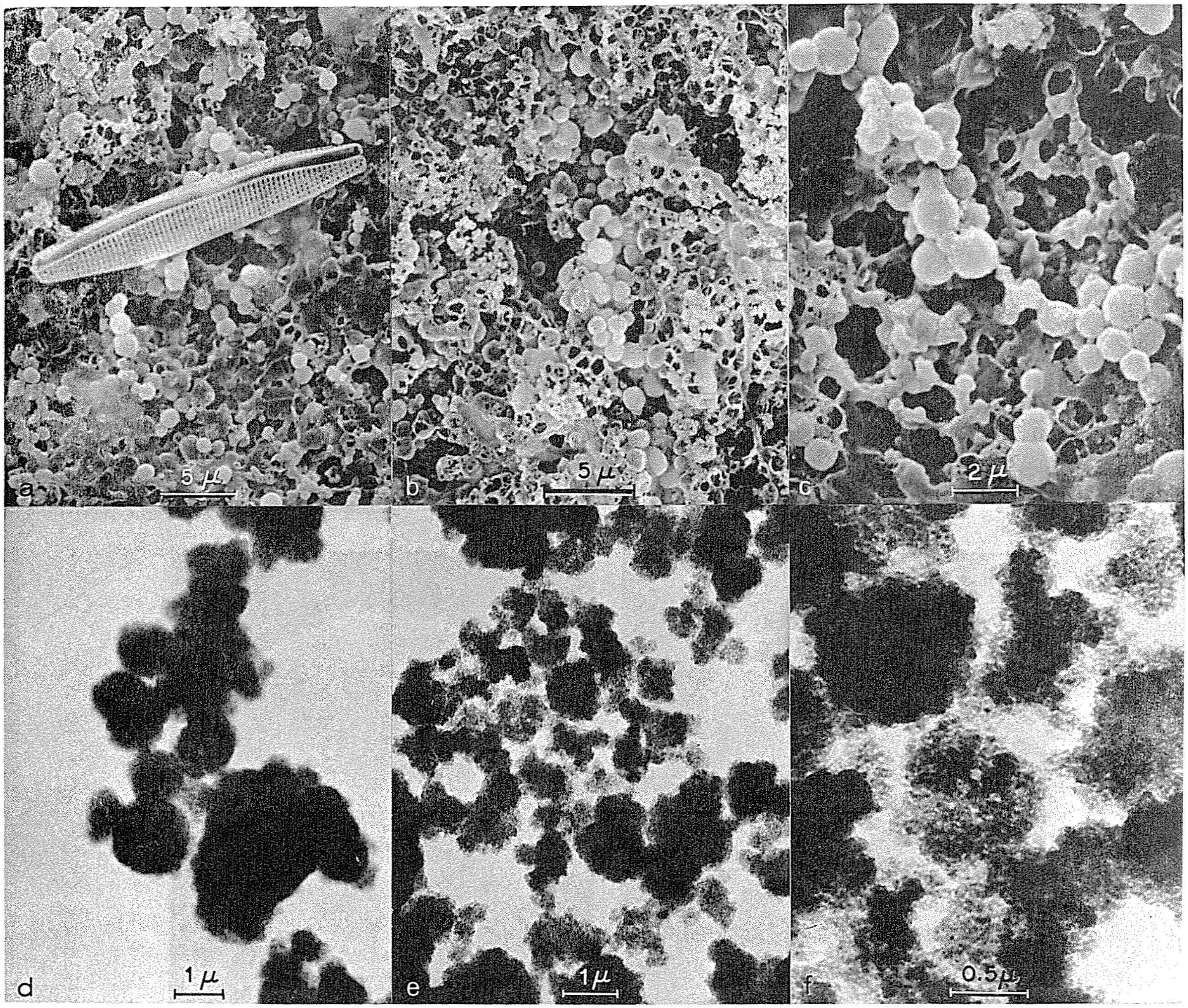

Figure 12

Electron micrographs of zinc sulfide globules which precipitated on millipore filters upon filtration of Lake Kivu waters collected below the O_2/H_2S interface. Graphs a, b, and c are made by scanning electron microscopy; d, e, and f are high-resolution electron micrographs.

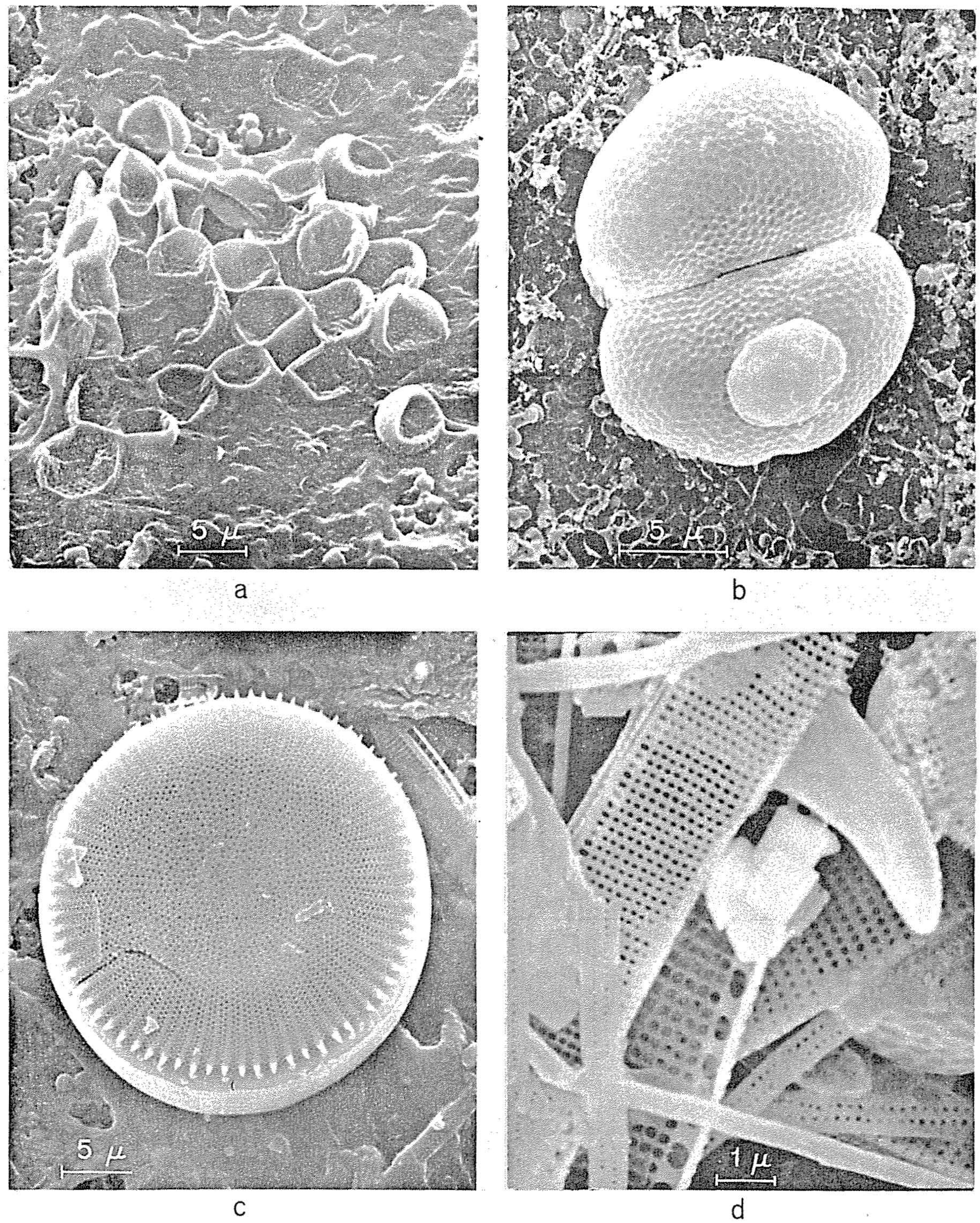

Figure 13

Scanning electron micrographs of suspended particles in surface waters of Lake Kivu. They show pollen grains (a and b) and diatoms (c and d).

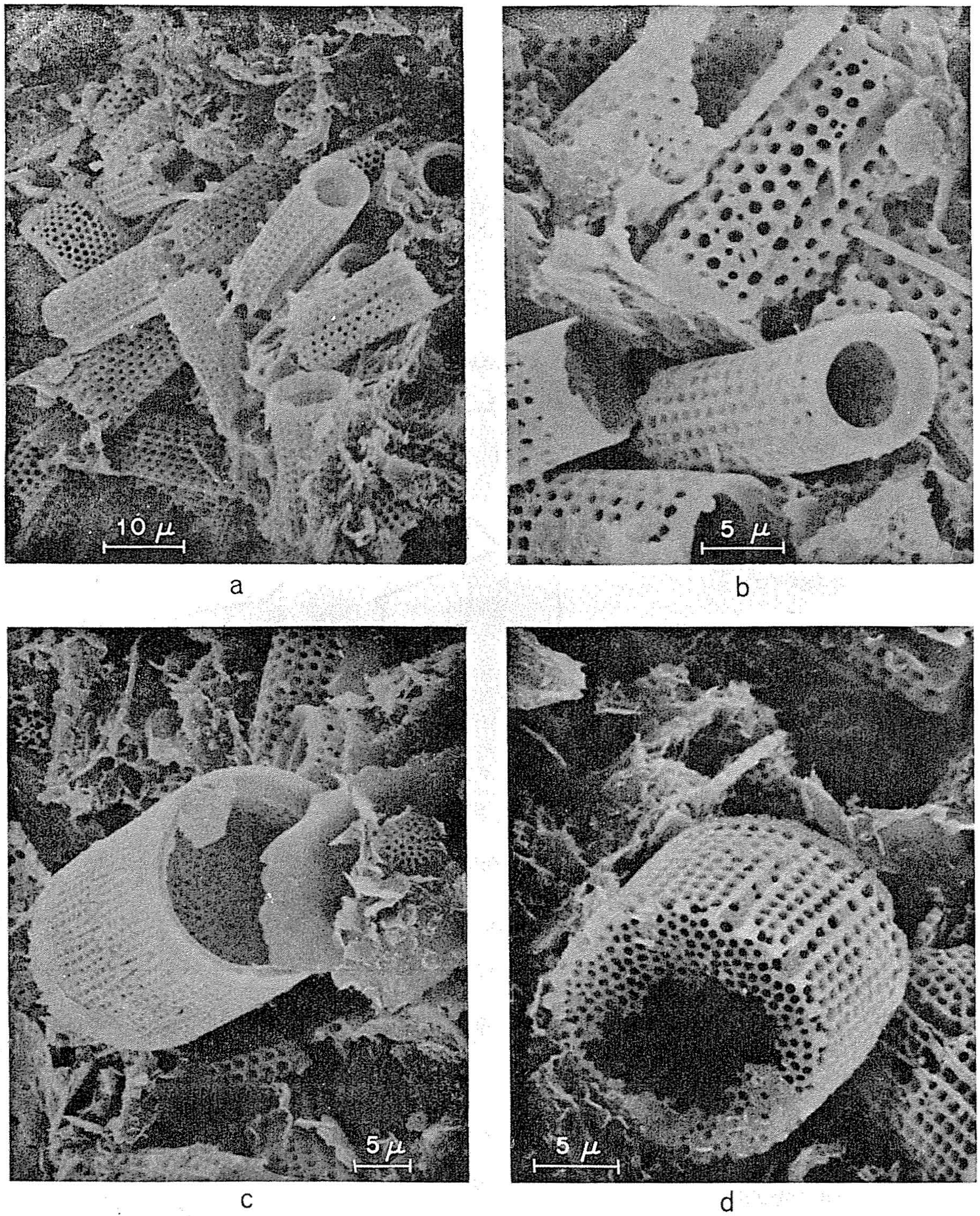

Figure 14

Scanning electron micrographs of sediment found on the isle of Idjwi about 100 m above present lake level. Different species of <u>Melosira</u> are present but none of <u>Nitzschia</u>, which is the most dominant diatom in recent Lake Kivu sediments.

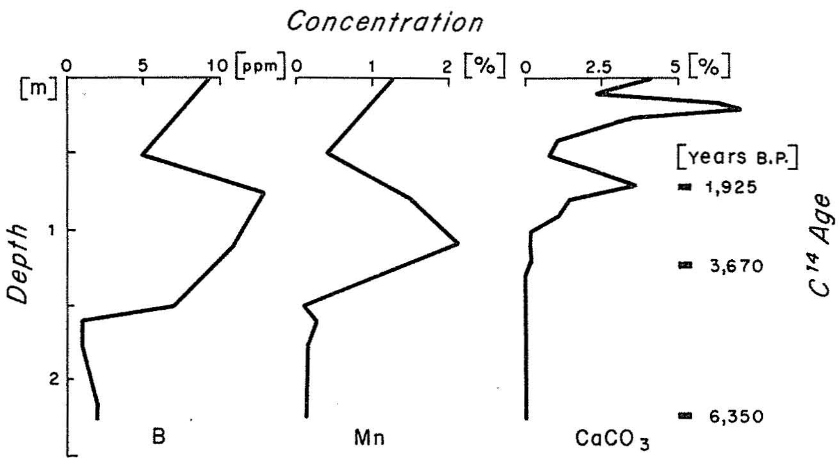

Figure 15

Distribution of boron, manganese, and $CaCO_3$ in Lake Tanganyika sediments from Station 3 (Southern Basin) (Degens et al., 1971). The water depth at this Station is almost 1,500 m. The increase in concentration about 4,000 years ago and continuing up to the present is linked to hydrothermal and volcanic events in Lake Kivu.

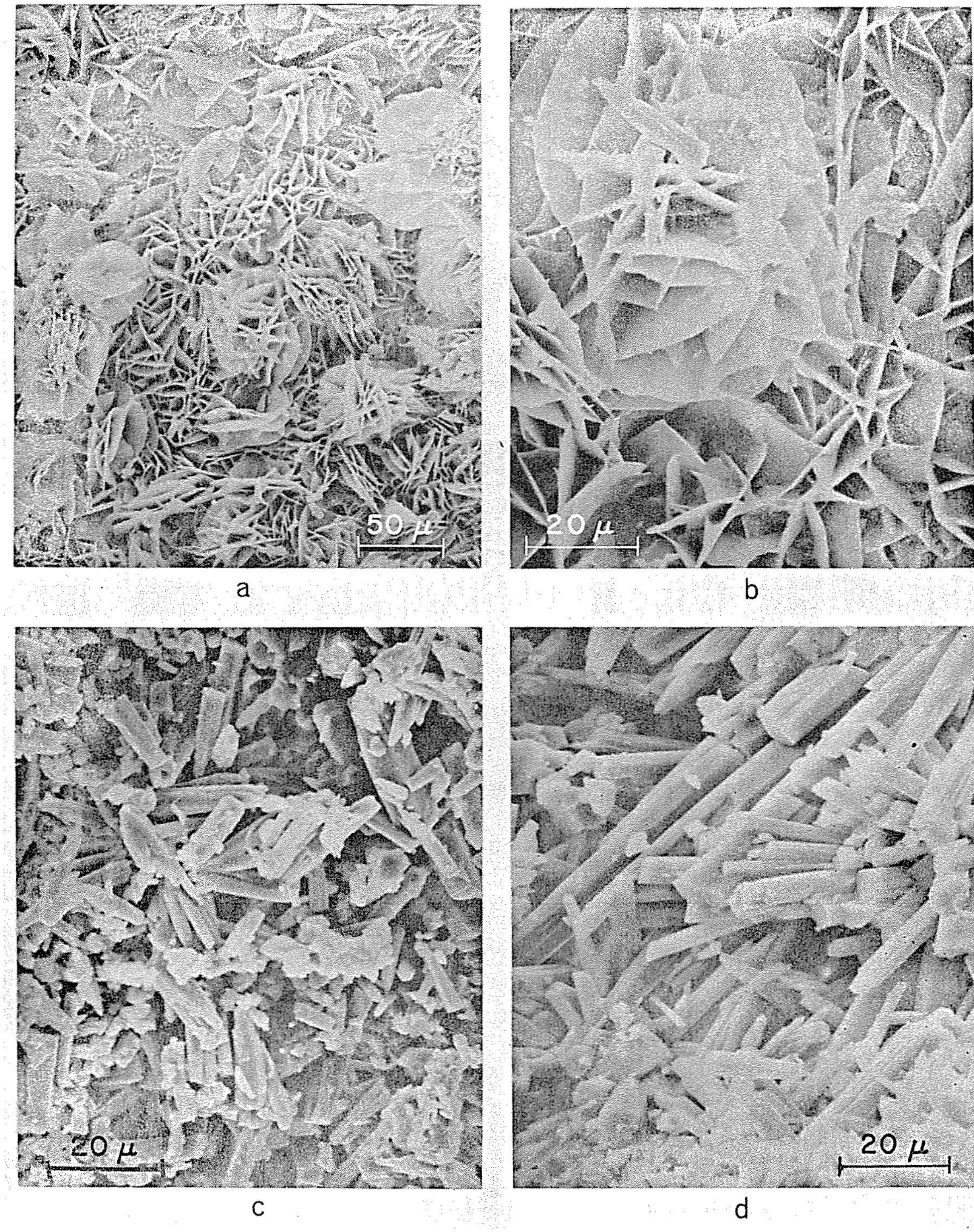

Figure 16

Scanning electron micrographs of aragonite, precipitated in Kakondo hot spring.

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7. Microbiology
8. Sediment Stratigraphy & Mineralogy
9. Sediment Geochemistry
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